

AUTOMATING CAPCOM: PRAGMATIC OPERATIONS AND TECHNOLOGY RESEARCH FOR HUMAN EXPLORATION OF MARS

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During the Apollo program, NASA and the scientific community used terrestrial analog sites for understanding planetary features and for training astronauts to be scientists. More recently, computer scientists and human factors specialists have followed geologists and biologists into the field, learning how science is actually done on expeditions in extreme environments. Research stations have been constructed by the Mars Society in the Arctic and American southwest, providing facilities for hundreds of researchers to investigate how small crews might live and work on Mars. Combining these interests—science, operations, and technology—in Mars analog field expeditions provides tremendous synergy and authenticity to speculations about Mars missions. By relating historical analyses of Apollo and field science, engineers are creating experimental prototypes that provide significant new capabilities, such as a computer system that automates some of the functions of Apollo's CapCom. Thus, analog studies have created a community of practice—a new collaboration between scientists and engineers—so that technology begins with real human needs and works incrementally towards the challenges of the human exploration of Mars.

*We know how to teach people how to build ships,
but not how to figure out what ships to build.*
—Alfred Kyle, quoted by Donald Schön¹

BACKGROUND

With our meager experience managing three-day lunar explorations, ranging over a few kilometers, barely more than a light-second from Earth, how can we confidently plan (or even imagine) year-long forays on Mars, where no conversations with Earth are possible and no infrastructure exists for shelter, communication, or resupply? Indeed, starting by imagining Mars surface explorations is at best good science fiction, prone to misconceived problems framed by imaginary solutions (e.g., how will people collaborate with robotic geologists?). We could start with a litany of issues (food, shelter, clothing)

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or technologies (electronic greenhouses, cave habitats, cybernetic spacesuits). But another approach is to proceed empirically—from baseline studies of contemporary field science on Earth^{2,3,4}; historical analyses of Apollo⁵ and space stations⁶; and “analog” missions, both historical^{7,8} and simulated^{12,13}. By proceeding from what we can do and have experienced in relevant terrestrial and space expeditions, we can identify gaps (e.g., the amazing lack of telemetry on the lunar rover), problems (notably, the impossibility for an Earth-bound “capsule communicator” [CapCom] to manage a Mars mission), and opportunities (e.g., using the Global Positioning System [GPS] to facilitate Mars navigation). From the perspective of human factors and technology design, we can relate baseline preferences for how scientists prefer to work on Earth to differences on Mars that will require changes in practice, especially new tools for communicating and documenting work⁹.

This chapter presents a methodology for operations research and technology development that proceeds incrementally from past experience and what we know how to do, to gradually address the challenges posed by long-term exploration of Mars. Rather than starting with what lies beyond the horizon, such as imagining the design of an “recreational vehicle” (RV) for week-long Mars excursions, we start by working from the edge of what we can already do and identify ways to extend it. For example, consider that during Apollo, astronauts were not permitted to walk into rilles. We must learn how martian explorers will safely study canyons within sight of their lander, before we worry about supporting their investigations on multi-day missions 20 km away. Similarly, we must avoid the “horseless carriage” approach of extrapolating today’s technology. It is all too easy for computer scientists, for instance, to focus on fancy interfaces for “geographic information systems” (GIS) to be used on Mars, when, as the study in this chapter shows, *eliminating* astronaut handling of GPS devices and coordinate databases is possible.

How, then, do we avoid aimless automation and fantastical, impractical designs? Obviously technology has changed a great deal since the days of Apollo, when a key job of CapCom was to ask the astronauts to regularly readout the picture frame number on their cameras or tell mission control the battery temperature of the rover. In the parlance of technology design, there is much “low-hanging fruit” for making Mars exploration easier than walking on the moon. But given the range of technologies and crew configuration issues we might consider, falling under the rubric of “artificial intelligence” and robotics, where should we begin? Based on five years of study of field science¹⁰ and analog missions^{11,12,13,14,15}, I suggest that automating some of the functions of CapCom on Apollo is a pragmatic first step. Further, the methodology that led to identifying this opportunity and implementing the capability illustrates a more general approach that can be applied to the multitude of other concerns a Mars mission entails, such as food and shelter. Thus, the example of automating CapCom illustrates how we can proceed incrementally from experience to identify problems within our grasp and, most importantly, invent new uses of technology than don’t merely make old ways of doing things faster or more graphically pleasing.

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In summary, the approach used here to preparing for Mars missions employs a *total systems perspective*, namely relating the environment, facilities, tools, organizations, protocols, scenarios, and so on to design a new *work system*^{16,17}. Rather than focusing on technology or human factors per se, we attempt to grasp the overall system of people working together and their environment. Rather than focusing on narrower views of “problems” such as “decision making under stress,” we consider a day in the life of a crew, so we can understand better the context in which plans are made and reformulated. Rather than promoting our favorite technology (e.g., using computer tablets for data collection), we begin by understanding how present technology interacts with how people prefer to work and where a better fit is possible¹⁸. Most of all, we do not begin with non-existent technology—“intelligent” computers being the most notorious—but with people in natural settings, on the moon, in an Arctic crater, or the Utah desert, using their imaginations to help operations researchers and technology developers understand how scientists normally do their work, what could be made easier for them on Earth, and what will be more difficult on Mars.

Subsequent sections of this chapter illustrate a range of methods that can be triangulated for automating some functions of Apollo’s CapCom: historical analysis, contemporary baseline studies of field science, scenario definitions, and field experiments with technology prototypes in simulated Mars extravehicular activities (EVAs). A broader thesis supported by this research is that multidisciplinary work at Mars analog settings is developing a *community of practice*—a network of scientists, engineers, and space mission specialists—who are learning how to work together and already establishing a practical path to Mars.

HISTORICAL ANALYSIS: APOLLO 17 LUNAR TRAVERSES

To date, the sum of human experience exploring a planetary surface beyond Earth amounts to less than two weeks on the moon by a dozen astronauts (1969-1972). How are we to extrapolate from this to support even a single month-long or 500 day mission to Mars? Much can be learned by studying the transcripts of the Apollo traverses^{19,20}. Perhaps the most striking observation is how CapCom—the astronaut in Mission Control in Houston, serving as the single point of contact for the lunar crew—was virtually a third person on the moon, often more present to the two lunar astronauts than they were to each other. CapCom maintained a continuous conversation with the astronauts, monitoring and advising nearly every step in deploying equipment, navigating, scheduling, regulating life support, logging data, and interpreting observations. With a bare 1.25 second delay, conversations were always possible, but sometimes confused because CapCom was managing two astronauts who tended to work independently. The rover’s video was controlled by another person in mission control and generally allowed mission control to keep an eye on one astronaut while working with the other. In retrospect, the functions of CapCom compensated for and largely hid the primitive technologies of the day.

To reveal the role and contributions of CapCom, I categorized and analyzed examples from Apollo 17 of the interaction between the surface EVA crew (Schmitt and

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Cernan) and CapCom (Bob Parker). This analysis is based on three segments of the second EVA during Apollo 17, termed “Orange Soil,” “Traverse to Station 5,” and “Geology Station 5 at Camelot Crater” in the ALSJ. Mission elapsed time is continuous from 145:23:48 to 146:56:34 (about 1.5 hrs). The excerpts were selected to identify the *kinds of assistance* provided by CapCom. The transcript was printed and annotated with written marks, then reformatted as shown here.

Analysis of the transcript reveals the following broad categories of information flow and work management functions as the EVA crew interacts with CapCom throughout their work:

- Reading out information (logging):
 - sample bag numbers
 - camera frame counts
 - rover systems indicators
- Asking where materials (cans, bags) are located
- Providing descriptions (geological, equipment condition) for the record
- Suggesting, requesting, or documenting equipment settings and usage (e.g., suit cooling, film magazine change, dusting radiators)

CapCom actively manages the work on the lunar surface:

- Indicates elapsed time, time remaining at a site, including walkback (turn around) warnings
- States revised plans for substituting, skipping, or reprioritizing work
- Provides navigation advice, including identifying craters the crew is seeing

These interactions occur in ordinary conversations, with many complications involving disruptive, misheard, and mistaken remarks. Typical interactions follow.

Sample bag numbers are provided to CapCom, often elaborated for a turn or two by both astronauts.

145:35:37 Schmitt: 511 has the gray from the other side of the orange band.

145:35:41 Cernan: And the other side happens to be the crater side.

145:35:46 Schmitt: That's right. North side.

CapCom has to be listening for information directed at him.

145:46:10 Schmitt: (To Gene) Okay, I got it. (To Houston) Okay, the basalt (from the large boulder) is in bag 512.

Frame counts are provided for both the commander (CDR) and lunar module pilot (LMP)

145:55:15 Schmitt: And, Bob, LMP is at (frame count) seven-five

The checklist mounted on their wrists details the planned route and activities.

146:10:11 Cernan: (Looking at checklist page....) Okay, and I want to go about (on a heading of) 120.

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The crew monitors their total EVA time, so they can make local judgments for using their time. The science backroom is providing schedule updates and suggestions to CapCom.

146:25:46 Cernan: How's our time, Bob?

146:25:48 Parker: Stand by. We're talking about that now. Stand by. You've got 25 minutes at this station, guys. We've given you somewhat of an extension here. You're using up some of it back at the LM, but we've given you somewhat of an extension. You've got 25 minutes at this station. The primary priority will be subfloor documented samples, and then subfloor rake soil. (Pause) As you can imagine.

146:26:26 Schmitt: Okay.

Warnings are given at 25, 15, and 10 minutes—sometimes interrupting the crew's conversation.

146:39:57 Parker: Okay, guys...

146:39:58 Schmitt: I'll get a...

146:39:59 Parker: ...looks like you'll be going in about 10 minutes.

CapCom must be able to hear "Yeah" as a response to him in this three-way interaction:

146:40:00 Schmitt: ...flight line photo. (Responding to Bob) Yeah. (Pause) (To Gene) Why don't you get a flight line...

How will we do traverses on Mars without a dedicated Capcom and science backroom one second away? Assuming that two or three astronauts are on EVA, we would like to avoid requiring someone in the remaining crew to monitor the EVA moment by moment over perhaps 7 or 8 hours. By assumption, the crew in the habitat will be busy with their own engineering and scientific work. Furthermore, for multiday excursions, it would be difficult to assign a person in the crew to monitor the external group for days on end. Could the CapCom function be largely automated, with reports sent to Earth regularly, and a loudspeaker alert sounding in the habitat when more direct supervision is required?

Obviously, computing technology has changed radically since the days of Apollo. We now have GPS, wireless telemetry (data and control connections between instruments and computers), and model-based software that can monitor, control, and diagnose systems automatically. The historical analysis of CapCom in Apollo suggests that most of the information-oriented functions (listed above) as well as many of the navigation and scheduling functions can be automated. We have prototyped these functions in a system called "mobile agents"^{†21} and tested the system experimentally in a simulated EVA scenario described later in this chapter.

[†] *Agent* here refers to a model-based program representing beliefs about the world and having conditional activities, hierarchically organized as situation-action rules. The agents are *mobile* because the computers are wirelessly distributed and attached to moving people or vehicles. See Ref. 37 and 38 for more information about the Brahms modeling and simulation system, which is the foundation for Mobile Agents.

Replanning according to scientific priorities, logistic, and safety concerns will be more challenging than automating tracking and data logging, but much can be done here, especially by facilitating the communication with the science backroom on Earth. For example, a program monitoring the Mars EVA could determine that the plan for the day will not be possible within resource constraints, and advise the people on Earth that a route choice will be required in one hour. Allowing twenty minutes for the message to be received (a near worse case) and twenty minutes for the scientists on Earth to make a decision, preferences could be communicated in time to make a difference. If this monitoring function were occurring on Earth, the situation might have only be appraised twenty minutes later (than a program could detect on Mars), and the advice might have been too late.

The historical analysis briefly described here shows how past experience can be used to identify appropriate uses for technology and to extrapolate how longer missions might be supported under more challenging circumstances. But indeed Apollo is not necessarily the best example of planetary geology, for the astronauts were considerably encumbered by their gloves and suits and restrictions on where they could walk. What will scientists on Mars really prefer to do? To understand this, we must begin by studying how field scientists live and work on Earth.

CONTEMPORARY FIELD SCIENCE BASELINE

Over the past half century, sociologists have studied laboratory science²² and scientific interactions in a community²³; plus cognitive psychologists have formalized what they called “scientific discovery”²⁴ in computer models that manipulate numeric data into equations. Other cognitive scientists have more broadly studied scientific reasoning based on analogy²⁵ and the nature of metaphor in inventive thought²⁶. Still broader studies of the history of science²⁷ consider the relation of models, experimental techniques, and conceptual change. But until the last decade, field science itself—the nature of expeditions and exploration—has not often been a topic of investigation. Using the ethnographic methods most often applied by anthropology, I have studied geologists and biologists in the Arctic and American southwest over the past five years (Ref. 10, 15). These studies include *baseline studies* (Ref. 12, 11)—observing science as it naturally occurs in Mars analog settings—and *mission simulations*—observing scientists participating as a member of a crew on a simulated Mars mission (Ref. 13, 14).

The topic of field science, or more generally scientific expeditions, is very broad. A study might embrace everything from individual planning and note taking to equipment storage, instrument repair, and use of computer logging devices. One can study human factors such as conversations over meals and forms of recreation to the use of individual space and work tent allocation. Under the rubric of *exploration*, even more remains to be discovered: how places are named, how people find their way, how routes are selected, why sites are revisited, and so on. And then an NASA mission specialist would want to log lengthy lists of logistics: how many batteries, what amount of fuel, and how many

meters of duct tape are required? Different studies are possible and many are certainly required to prepare for a Mars mission.

My own investigations have been most fruitful in considering how scientists interact during traverses, while they are out observing, deploying instruments, and collecting data. This may be done by walking or with all terrain vehicles (ATVs).[‡]

In the discipline of cognitive science the idea of “collaboration,” occurs frequently, especially when considering computer tools. Anthropologists and sociologists consider how collaboration occurs informally^{28,29} and work with computer scientists to develop “workflow tools” that could make collaboration easier. Consequently, in following scientists around Devon Island or in the Morrison Formation of southeast Utah, I hoped to study collaboration.

My studies of scientists working together in the field, as well as living and working in habitats under mission simulation conditions, show that not all instances of working together are forms of collaboration. Indeed, a distinction can be drawn between *coordination* (adapting plans to share resources), *cooperation* (adapting methods to pursue independent goals without interference), and *collaboration* (adapting goals to formulate new ideas or invent new products). This distinction is important because if we do not understand the nuances of how people work together, we will be chasing windmills in trying to create the most challenging technologies (e.g., robots that collaborate with people[§]) and then not using existing technology to its best advantage in helping people (e.g., helping people allocate resources).

Put another way, our imaginary scenarios of Mars exploration and extrapolations of technology must be grounded in a proper scientific understanding of how people think and work, with an equally scientifically sober formulation of what computer technology accomplishes and how it works. Unfortunately, decades of loose talk about computer “intelligence” and “knowledge-based systems” has confused how model-based software works and how its capabilities differ from human cognition^{30,31}. This is a shaky engineering foundation for supporting six people living on Mars. A fair appraisal of the differences between people and machines is required—and this begins by direct studies of scientists in natural settings, doing field science.

[‡] The Mars Society Michigan chapter has also adapted a military truck as a simulated “pressurized rover,” for multiple day excursions (Ref. 34).

[§] Today’s model-based programs manipulate representations of concepts, encoded as text networks, variously called “semantic networks,” “conceptual graphs,” “frames,” or “rule-based systems.” Using such models of concepts, computer programs are capable of routine forms of formal problem solving, natural language comprehension, systems design and control, etc. But model-based programs are ontologically bound by the text definitions provided by people; the programs are not capable of *conceptualization*, that is, relating multiple modalities of perception and action into higher order categories of conceptual systems (Ref. 30 and 31), what we informally call “forming new ideas.”

I present here two short examples of what we can learn from the ethnographic studies—following scientists around with wireless microphones, recording their conversations, videotaping their interactions, and interviewing them about their intents and discoveries. For other examples, see Ref. 10.

Geologist Collaborating with Biologist

In July 1999 a biologist (C) and a geologist (Z) were together in Haughton Crater for over three weeks. Over the course of 18 days studied systematically, they each left base camp for 21 traverses, but rarely traveled together. In cognitive psychology parlance, Z employed a *breadth-first search*, visiting 14 sites once, while C's exploration was *depth-first*, visiting 3 sites only once. In the traverse excerpted here, C and Z have chosen to go together on a traverse, with the intent of identifying rocks with endoliths (having life growing inside, just below the surface layer). The example illustrates scientific collaboration, but shows that the relationship is not always symmetric. Z, the geologist, is collaborating with C in pursuing biology objectives, while C learns nearly nothing about Z's geology investigation. (Clock times appear in brackets []. Indentation shows talking simultaneously.)

Throughout C acknowledges Z's independence, while making his biology interests known:

C: These are the same stuff? You want to get one? (Z hits and they look together)
[11:58]

C: If you find any [rocks with a white calcium carbonate crust]... bring them back.

Then C states another personal objective:

C: What I really want to find is an endolith inhabiting the subsurface of a shattercone! [11:59]

Z: (laughs) That would be quite funky.

With an interest in limestone endoliths, C asks whether a shattercone can be limestone:

C: Can you get limestone shattercones?

Z: Oh most them you see lying around are limestone...

C: Oh, really? Okay.

Z: All the black stuff's limestone.

C: Why is that black and this stuff is brown?

Z: (garbled)

C: Okay, different crystalizations or something...

Z: (garbled) yeah, probably different... (garbled)

C summarizes his understanding:

C: So there should be quite a high chance of finding some endoliths in a limestone shattercone...

As they are walking, C again reveals how what they are doing relates to his research interest:

C: So leads on to, ah, Mars stuff, you know, looking at, ah... [12:13]

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Z: um, hmm

C: ...impacts, impact craters as a preferential site...

Z: Yeah

C: ...of life on Mars...

Z: Yeah

C: For colonization....

The following illustrates very nicely how Z identifies samples and provides basic tutoring on geomorphology, according to C's immediate interests:

C: (pauses again at a rock) Saw orange in there... So what is that? [12:20]

Z: Actually, I'm not sure what that stuff is.

Z: That's probably recrystallized calcite actually. [12:21]

C: So where does gneiss come from?

Z: It can be, you can get metamorphic anything, so it could have started out as volcanic or sedimentary

C: Okay, this is the generic metamorphized rock? (somewhat humorously)

Z: Yeah, gneiss is sort of like high-grade rock, sort of like slates, slates are low-grade metaphoric rock... (continues to give more detail)

C reveals another interest, and asks Z to assist:

C: It's a good breccia pile... that's another thing I want to find... endoliths in breccia...

You want to smash that one? (hands over) [12:24]

Z: ... quite a nice bit.. mostly a big clast by the looks of it.

C: Yeah (both are looking at rocks)

C introduces a term, showing he has some geological knowledge:

C: A hydrothermal one? [12:25]

Z: Possibly, yeah, or it could just be corroded.

C's subsequent questions are similar, to understand the relation of samples to the impact event:

C: This gneiss here, (looks) is this shock-altered?

C: So how did this get to the surface? From the impact... No, that's too deep?

C: Yeah, wow, so, okay, so you would not see this if there had not been an impact, you would not find it in the rest of Devon... bits of gneiss laying around...?

Atypically, Z volunteers what he is observing:

Z: Oolitic limestone (to himself)... hmm, this is an oolitic limestone...

C: An oolitic limestone.

Z: (garbled)

C: What is that a mixture of?

Z: Tiny sort... concretions of... and the limestone...

C: How does that come about?

Z: They form generally on..

C: ...oh yeah!

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Z : ...tropical
seas...quite, it's like minute grains of sand or something...just roll around on the
sea bed... concretions...
C: It seems quite dense...
Z: Yeah
C: It's really sort of amazing...
Z: (hits with hammer in different ways) It's hard to break... (laughs) [12:30]

As further evidence of the asymmetric nature of the collaboration, C lists Z as a co-author of his research during this field season, while (quite appropriately) Z does not list C. The example shows transparently that the term “collaboration” does not apply to every instance of people working together. The month-long investigation showed that geologists and biologists may not want to go to the same places on Mars (should there be a biological study of Mars!). As we develop tools for naming places and making voice annotations (Ref. 21), we should realize that the crew may not need to immediately share all their data, but some investigations may be collaborative. And further, no robots will be collaborating with people anytime soon—at least not until they have a high order of consciousness, enabling them to have their own personal projects (Ref. 20). And why would we want to have robots carrying out *their own* scientific work? It will be difficult enough to get machines that can help us all, and not all advantageous to create artificially officious competitors.

So forget robot collaboration. What kind of assistance do people need? How might robotic assistants *co-operate* with each other?

Biologist Assisting Biologist: Navigation Example

One of the most common (and often humorous) experiences on expeditions is getting lost, or at least not knowing exactly where you are or what route to take. Field explorers today commonly use GPS devices. But hours are wasted remembering how to use them, waiting for satellites to register (more difficult in canyons or in polar latitudes), or in relating barren terrains to maps flapping in the wind. Crews in mission simulations spend hours learning how to use GPS devices and read maps marked by previous crews (Ref. 15). A frequent problem is confusing the degree-based coordinate system with the metric (UTM) system and even variations of these. After over 100 scientists visited the Mars Society's Mars Desert Research Station (MDRS) in an 18 month period (December 2001 – May 2003) the shared map's transparent overlay had to be oddly aligned on each use, to interpret points plotted in different coordinate systems.

A typical example of the difficulty of using GPS devices occurred while C was exploring some lakes with D, a biologist-oceanographer. They had been dropped by helicopter to the east of Haughton Crater on Devon Island and had just walked to a nearby lake out of sight of the helicopter. They are looking at a map.

C: It must be over the ridge here. It's amazing how difficult it is to find things.... Is it that one there?

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D: Yup.

C: Is that it? It's Lake Madagascar. So I think (it must be?) other there.

D: So that's where we are now?

C: Well, think we're here (points to map), aren't we?

D: Um-hmm.

C: (Moves finger slightly) On the edge here.



Figure 1. C points “on the edge here”

D: Right (hesitantly)

C: Is that right? (motions with finger) We just walked around here. (points to lakes above) So there's these.. and then this one (pointing to lower large lake)

D: Um-hum... where is the... all right...

C: (reaches into pocket) Let's get a GPS fix on this.. (expletive) run out of batteries

D: Is it?

C: Well, actually (mumbled) (Opens map) Why don't we check the coordinates of this thing?

D: (preparing to write label on vial) Want to just call it Madagascar on here?

C: Yeah. (Map flaps in wind) Will you take that GPS unit? (holds over to D, waiting for him.. then pulls attachment away from self) Extend that little dog leash..

D: (unclear)

C: Okay so this should be 89 degrees...15 minutes (reads map)...this should be...75 degrees... one...

(Both are looking and waiting for GPS unit to respond)

D: 21 minutes

C: Okay and what the (unclear) reading..?...

D: 15.81..

C: 15... (points at map) yeah, Lake Madagascar, because that's 15.. point 81.

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(They point at the map together)



**Figure 2. Biologists point at the map together
(C's index finger on left; D's pinky on right)**

C so yeah, so we have come over... the other one is here... that direction (motions to right distance)

D: So just on the other side of the helicopter?

C: Yup. Do you want to (unclear) with that? (folds map)

D: Three down.

C: Cool. That should do us... after that third one.

In this excerpt, D assists C by holding the map and GPS unit, and then reading out the coordinates. This is sufficient for C to identify their location and thus the name of the lake. They physically coordinate the materials, as C cooperates in adjusting how he holds the map and uses the GPS unit. (For example, as the device is tethered to C's pocket, D avoids pulling C into the water by jerking the device abruptly.) But they do not engage in any collaborative work, in the sense of adjusting their goals to create a new project.

Besides fumbling with maps and GPS devices in the field because of the wind, cold, or gloves, people tediously have to log, map, and lookup coordinates to record and plan EVAs. Some researchers are working to automate the logging and mapping process, focusing especially on the interface of the Geographic Information Systems (GIS). And indeed, even the simplest devices can display a path, store routes, and provide direction information for getting back to a named place. However, rather than making these manipulations easier by focusing on the interface, a better strategy is to eliminate human contact with GPS devices and awareness of coordinates to the fullest extent possible. In other words, we should hide the GPS process, much as computer networks hide the "internet protocol" (IP) addressing scheme by which individual computers are registered

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and addressed on the world wide web. By analogy, a GPS coordinate should be like an IP address—something you don't routinely know. Accordingly, a central function of the automated CapCom system we have developed is to make GPS tracking invisible, so people can name places and later receive a map of where they have been, allowing direct indexing of the samples logged, voice annotations, and so on, without having to repeatedly reference the precise coordinates.

SCENARIOS FOR TESTING TECHNOLOGY PROTOTYPES IN SIMULATED MARS EVAS

The historical and baseline studies, besides revealing needs and opportunities for technology development, are also revealing where and when technology must be used. In some sense, this may sound like a trivial conclusion; for example, it may appear obvious that field scientists need navigation advice during an EVA. However, the studies reveal that *topographical constraints*—the landforms in which geology in particular occurs—pose significant constraints for technology. In particular, few robotic systems in existence today can go where geology is actually done: on scree slopes, up against outcroppings, along rough cliff ledges, and into steep narrow ravines. Furthermore, geologists at MDRS routinely walk 100 meters from their ATVs, constraining how their spacesuits (if they were on Mars) might interact with life support, power, and communication gear on their transportation vehicles.

To illustrate these points, consider three sites near MDRS chosen (during Rotation #5, April 2002) for testing the aforementioned “mobile agents” system (during Rotation #16, April 2003). The first site involves walking into narrow, winding V-shaped ravines, with a bottom of barely one shoe-width, preventing ATV access (Figure 3).



Figure 3. Typical narrow ravine of Morrison Formation, just behind the Mars Society's Mars Desert Research Station (MDRS). Foot path indicated by arrow is about .2 m wide; ravine is about 3 m below foreground ledge.

The second site (Figure 4) involved walking on a slope of loose sand and rock at the angle of repose, requiring the ATVs to be left 50 meters below, and out of sight of the work area on the (Cretaceous Period) plateau.



Figure 4. Oyster Fossils scenario: Astronauts during MDRS Rotation #5 simulating EVA climb steep slope, leaving behind ATVs (indicated by circle).

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The third site, called Lith Canyon by MDRS crew members, involved broken ledges and steep cliffs (Figure 5). During an experiment with the automated CapCom system at this site, the topography created several serious topographic problems:

1. The wireless computing system was unable to cover the entire area, causing a “shadow” at the head of the canyon, causing the computerized backpacks to drop out of the network linking the astronauts back to the MDRS habitat.
2. The astronauts were unwilling to pass over a meter-high dropoff in the canyon, requiring them to change their plan and walk around.
3. The EVA Robotic Assistant (ERA³²) was unable to follow the astronauts into the canyon because of the terrain, and even along the ledge had to be directly teleoperated with a person standing nearby (called a “robo-chase”).



Figure 5. Lith Canyon scenario: Two geologists simulating astronauts on an EVA during MDRS Rotation #16 walk around a dropoff to the left (indicated by circle); the ERA has been physically maneuvered by its human handlers to the ledge at the right (arrow)

As we learned from the beginning of our work in the Arctic (Ref. 11), the topography of field science sites is a very strong constraint, providing new meaning to the rubric (first developed in office settings) of “design in the context of use” (Ref. 16). Here the context is *physical* in three dimensions and must be respected. Indeed, any geologist knows that today’s teleoperated exploration of Mars is strongly restricted by where the landers can land and where the rovers can roam. What is perhaps less known is that few robots today can operate in the types of terrain where geology is actually done (a possible exception was Carnegie-Melon University’s Dante II rover, “a tethered walking robot, which explored the Mt. Spurr [Aleutian Range, Alaska] volcano in July 1994”³³).

The Lith Canyon field test was a milestone for the Mobile Agents project and a perhaps historic moment for the advancement of Mars exploration. The geologists shown in Figure 4 are each wearing computers on their backpacks, to which they communicate with voice commands. The computers are wirelessly networked to another computer on an ATV above 75 m on the ledge to the left (out of picture), and from there to a laptop running in MDRS more than 5 km away (Figure 6). Simulating an EVA, the geologists told the computer what activity they were doing (from a predetermined list), named places, recorded voice annotations, and took photos—and this information was sent to MDRS and then out as email via satellite to people representing the “remote science team” (RST). The system tracked their location and biosensors, and gave alerts when these readings were off-nominal. Location and health data was transmitted at set intervals via email to the RST, and although a software bug prevented all data from being transmitted, the first photo arrived successfully vial email. The test showed that the voice commands were useful, and related to the historic and baseline studies, indicated that a reasonable first approximation of CapCom’s functions had been achieved.

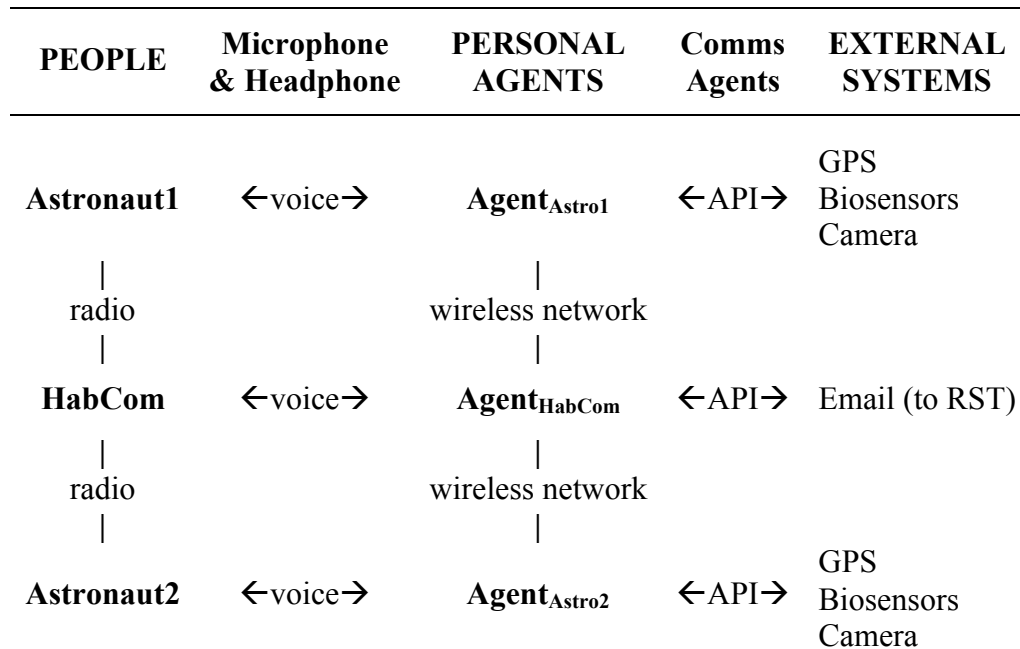


Figure 6. Simplified schematic of automated CapCom implemented in Mobile Agents architecture: Astronauts and HabCom communicate with each other via radio; people speak to their Personal Agents on local computers using a microphone and receive feedback on their headphone. Personal agents are communicating locally with external systems via “communications agents,” providing an Application Programming Interface (API) to read data and control devices (e.g., camera). Finally, Personal Agents (implemented in Brahms on different computers) communicate with each other via a wireless network (with repeaters) using an “agent registration” system, similar to how computers communicate on the web via IP addresses.

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At the same time, the field prototype experiments revealed potential issues (e.g., the astronauts worked independently, not on a voice loop as in Apollo), and desirable new functions (e.g., allowing them to record a conversation as a “voice note”). The scenario confirmed that the topography of field science poses severe constraints for robot design, and that a robot that could carry an antenna-repeater, to keep the astronauts’ backpack computers on the wireless network, would be very useful. Just as the historical analysis showed that it would be useful for robots to hold open sample bags for people, our automated CapCom experiment showed that we should focus on how machines can help people, rather than trying to develop the most complex, anthropomorphized tool we can imagine (e.g., something with arms and hands that can pick up rocks). This is not to rule out technology research of any sort, but to emphasize that pragmatic applications—building tools that can assist people with known problems—should be our first priority. Someday we will almost certainly develop a robot with the capability of the human mind and body, but if we have human concerns and goals in mind, we will first seek to help people, not replace them.

CONCLUSIONS

The historical study Apollo’s CapCom, plus baseline studies of field scientists (both in unencumbered exploration and simulated mission modes), suggested that we transcend present-day GPS data manipulation, to facilitate exploration by automating some route finding and tracking tasks. Broader study of people working together allowed us to formulate a computer system in a pragmatic, scientifically grounded way—not replacing them, not providing an robot buddy, but simply focusing on information processing to make field science easier. Accordingly, we have created a prototype computer system to track and monitor astronauts during an EVA, using voice commanding for logging scientific data. In particular, we have used a combination of model-based and speech recognition technology, with sophisticated “agent-based” wireless networking, to begin to automate some of the functions of CapCom.

By avoiding hyperbole such as “computer collaborator” we can more fairly convey what has been accomplished, and properly relate people and machines in the resulting work system. Accordingly, we use the term “automating CapCom” always with qualification, having first distinguished some of CapCom’s contributions (e.g., replanning and scientific data interpretation) that require value judgment that today’s model-based programs cannot do. This enables us to properly design a comprehensive work system that reserves certain activities for people, and indeed views these contributions as constraints that must be considered in the overall design of communications, EVA procedures, and tools.

As posited by the introduction, the work system design methodology employed here starts with people in authentic work situations to empirically identify real needs (“empirical requirements analysis” and “design in the context of use”). On this basis, we can incrementally identify new functions and invent appropriate technology that extends our exploration capability, step by step. This pragmatic, grounded research and development strategy may be complemented with futuristic envisioning (science fiction)

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about long-duration Mars missions. For example, interesting stories can be told of how a “pressurized rover” (RV) like the Mars Society’s Everest project³⁴ might be used to explore a great distance over multiple days from the Mars lander. But we have much still to learn before we know what technology to build. What distance might geologists wish to cover in the first week or month? Would a scientist-astronaut be content to spend several weeks in one place, while other crew members investigate other areas (i.e., subgroups travel together)? What does the biologist need to know about the geologist’s daily work? If a “robot scout” were fully teleoperated (from the Mars habitat), what percentage of the preliminary exploration could be done without going outside? Besides simulated missions with people, one may also seek to answer these questions by simulating the missions in “virtual worlds,” where all the actors are synthetic, computer-based “agents”^{35,36}, as we have done in the Brahms system^{37,38}.

The experience of multidisciplinary field expeditions, involving scientists and engineers, suggests that we can rapidly develop technology using today’s computer and communications systems, which will be genuinely useful and indeed needed for Mars exploration. This “naturalistic” approach—which has changed how computers are applied in work settings, how psychologists study cognition (e.g., the discipline now called “naturalistic decision making”), and how social and cognitive scientists work together—comes at a good time. For this confluence of design perspectives and critical pragmatic approach to automation³⁹ is almost certainly necessary if we are deal with the challenges of building reliable systems for a multiyear Mars mission.

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